NEW ELECTROMAGNETIC SENSORS FOR DETECTION OF SUBSURFACE CRACKING AND CORROSION

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INTRODUCTION

There have been many improvements in electromagnetic NDE for aging aircraft in the last few years. These improvements include rapid eddy-current scanners [1], magneto-optic imaging [2], pulsed eddy-current methods [3], self-nulling probes [4] and superconductive quantum interference devices (SQUIDs) [5].

While each of these technologies contributes to the overall improvement of airworthiness assurance, none offers the combination of low-cost, ease-of-use and high-sensitivity needed to increase both the probability of detection (POD) and the probability of inspection (POI) for deeply buried cracks and corrosion.

TPL has developed a prototype NDE system based on a self-nulling, magnetoresistive sensor for low-frequency inspection of electrically conductive materials. This new system offers high-sensitivity, high spatial resolution and low-cost. Furthermore, the system's non-contacting, self-nulling configuration allows the probe to be used on painted and irregular surfaces by personnel with minimal training.

NOISE LIMITS OF CONVENTIONAL COIL-BASED EDDY-CURRENT

The most obvious source of improved coil performance is to increase the coil response sensitivity, or responsivity. The responsivity of a sensor is the slope of the voltage output versus the parameter of interest. In the case of a coil it is most fundamentally described in terms of Volts per Oersted. To increase the responsivity of a coil, the magnetic flux through the coil must be increased. The flux through a circular coil can be described by

$$\Phi_m = B\pi r^2, \quad (1)$$

where B is the magnitude of the magnetic field perpendicular to the surface defined by the coil radius and r is the coil radius. While it may appear that the improvement in sensor performance will increase in proportion to r^2, one must first consider sensor noise sources.

A fundamental limit on the sensitivity of an eddy-current sensor is the Joule heating in the material caused by the eddy-currents. This form of Johnson noise can be approximated by evaluating the resistance in a volume interrogated by the applied magnetic field.

A coil will typically generate a field which is applied to a region of material having a radius slightly larger than that of the field generation coil. In the case of a well-shielded coil we can assume that this area of regard is approximately equal to that defined by the coil radius.

The depth of penetration of the applied field, often referred to as the skin depth, is inversely proportional to the frequency of the applied field. This skin depth, along with the area of regard, will be used to estimate the volume through which current must flow (Figure 1).

If the material under test has an electrical resistivity, ρ_{elec}, then the root-mean-squared voltage noise caused by the eddy-current Joule heating within the material can be approximated by:

$$\Delta v_{rms} = r\sqrt{4\pi k_B T \Delta f\, \delta \rho_{elec}} \ . \quad (2)$$

Here r is the radius of regard, T is the temperature in Kelvin, k_B is Boltzmann's constant, Δf is the bandwidth and δ is the skin depth. While the permeability dependence of the skin depth has been omitted here for clarity, it is important to note that increased field penetration also increases the thermal noise.

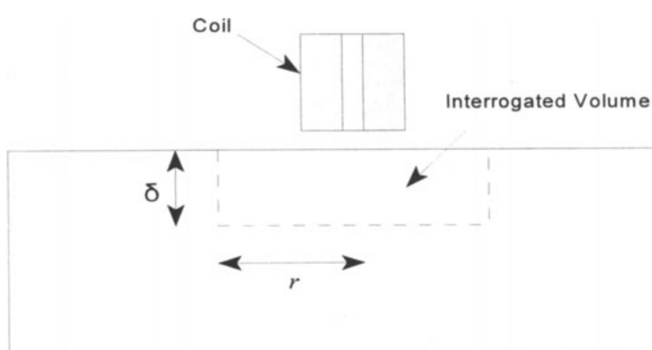

Figure 1. Volume of material used to define the thermal limit.

The relationship of immediate interest in Eq. 2 is that the thermal noise limit of the material is proportional to the radius of regard. Obviously one must consider other noise sources such as thermal noise in the pickup coil, transformer and amplifier electronics in order to estimate the fundamental sensitivity limit, but it is clear from Eq. 2 that larger diameter coils will have higher thermal noise limits.

Fortunately, although the thermal noise limit of the material increases in proportion to r, the flux increases in proportion to r^2. This means that higher sensitivity can be achieved by building larger coils, although the increase is not as dramatic as one might first expect.

There is another fundamental relationship that will affect coil responsivity. The flux through a coil can only generate a current in the coil if the magnetic field changes as a function of time. Specifically, the curl of the electric field vector, which generates the current flow in the coil, is defined by the change in the magnetic field orthogonal to the plane of the coil as described by Maxwell's equation:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}. \tag{3}$$

This equation demonstrates the fundamental problem associated with using coil-based sensors to detect low-frequency magnetic signals. As the frequency of the applied signal is reduced, so is the rate of change of the applied magnetic field with respect to time. This, in turn, reduces the coil current.

The sensitivities of conventional coil-based eddy-current sensors are limited primarily by the large dimensions required to increase responsivity and by the fundamental reduction in responsivity at lower frequencies.

In order to address the performance demands of inspecting aging aircraft, sensors with high responsivity, particularly at low frequencies, and high spatial resolution are needed. Coil-based sensors are fundamentally limited and cannot meet the high performance requirements of airworthiness assurance.

CONVENTIONAL SELF-NULLING PROBES

The concept of a self-nulling probe for eddy-current inspection is not new. A self-nulling probe offers two significant advantages over absolute-mode sensors: 1) self-nulling probes typically have greatly reduced noise compared with conventional probes and 2) they operate in a simple "go / no-go" fashion which eliminates the need for a highly-trained operator.

Self-nulling probes, however, must not be viewed as a replacement to all other inspection methods. They are, instead, a tool for rapidly locating regions that will require further inspection. If they can be made small and cost-effectively, all aircraft inspection team members could carry one to augment their training in visual inspection.

The critical design limits of self-nulling probes to date have been the need for electrical contact with the underlying material and the high sensitivity to lift-off caused by irregular surfaces. Any technique that requires removal of paint and is poorly suited to inspection of irregular surfaces will not prove cost-effective for airworthiness assurance applications.

A small, battery-powered, self-nulling probe that does not require electrical contact with the substrate, has much improved sensitivity over coil-based sensors and can be made cost-effectively would provide a new tool for rapid, highly-sensitive detection of sub-surface cracking and corrosion by personnel with minimal training.

OVERVIEW OF APET

Under a Phase I Small Business Innovative Research (SBIR) program sponsored by the National Science Foundation, TPL has developed a new probe which promises to improve the speed of inspection while dramatically increasing the probability of detection (POD) for subsurface cracks and corrosion (Figure 2). This new sensor is a non-contacting, self-nulling probe that is very sensitive to the low frequencies needed for detection of sub-surface anomalies.

TPL's APET sensor uses magnetoresistive (MR) materials in place of conventional coil magnetometers. Unlike coil-based magnetometers, MR sensors exhibit low 1/f noise and high sensitivity from DC to the GHz region.

Another key advantage of MR technology is low cost. The critical component of MR devices can be fabricated for less than $10 and does not require cryogenic cooling as do

Figure 2. The battery-powered, APET controller and sensors.

SQUIDs. While the theoretical noise-floor of SQUIDs is typically superior to that of MR magnetometers, they are quite costly, complicated and they are not self-nulling.

RESULTS TO DATE

In one experiment, TPL used the APET-CR sensor to scan a riveted aircraft skin sample provided by the FAA/AANC. Figure 3 shows scans of two adjacent rivets in that sample. The first rivet in Figure 3 contains two defects: 1) a 173 mil long crack (~4 mil wide) originating at the right side of the rivet, 2) a 28 mil long crack (~4 mil wide) under the rivet head. The second rivet in Figure 3 is a good rivet with no defects. By subtracting the normal rivet data from the first rivet image, the presence, location and dimension of the two cracks is immediately apparent. This gives the operator conclusive evidence of a defect that is extremely difficult to detect with conventional probes.

Figure 4 shows a photograph and scan data from a 6061 aluminum sample (provided by the FAA/AANC) which has a circular region of corrosion with a nominal 10% thickness loss and a 2.5% total thickness scale region outside the corroded region. The sample was scanned from the side of the aluminum panel opposite to the corroded region through approximately 40 mils of aluminum. Both the boundary of the corroded region and the pitting within the region are clearly visible. The scan even shows some scaling in the region outside the corroded area.

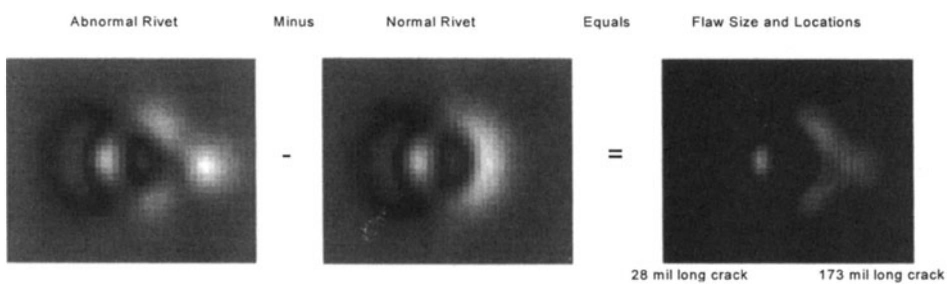

Figure 3. Deconvolution of a normal rivet and a rivet with cracks.

CONCLUSIONS

A new, self-nulling probe has been demonstrated. Realistic crack and corrosion defects have been imaged with high signal-to-noise ratios. This new probe offers low-cost, high sensitivity and high spatial resolution. It does not require electrical contact with the test material and is simple to use owing to its self-nulling configuration.

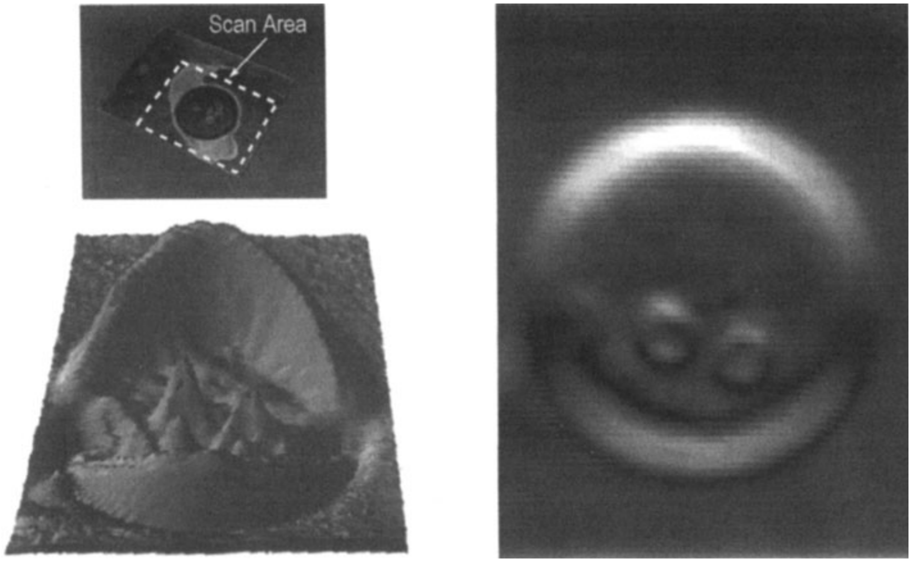

Figure 4. Corrosion sample and scan data rendered in both 3D and 2D. All data was collected on the side opposite the corrosion.

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